Future Beam Technologies

Optical Probing & Control of Phase Space

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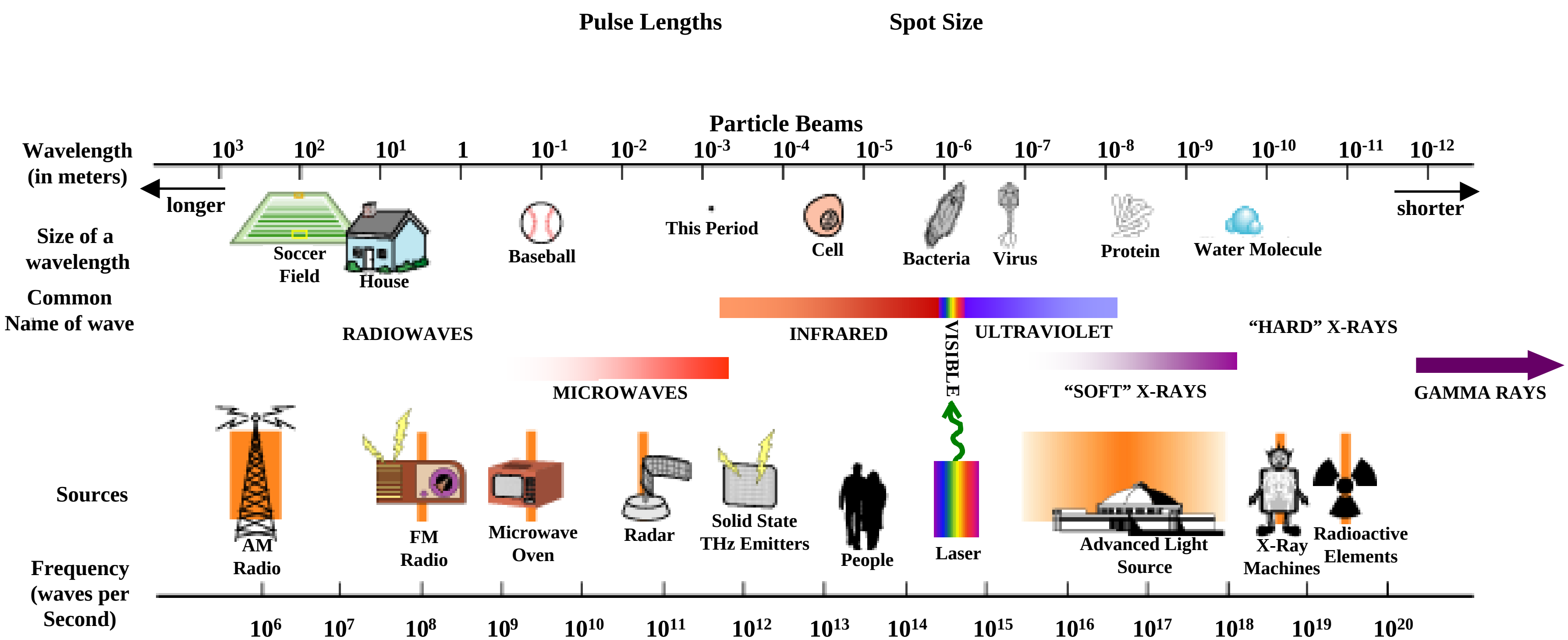
Outline

- → Motivation for control at optical scale
- → An example of optical slicing
- → Applications of optical probing & control
- → Optical stochastic cooling (OSC)
- → OSC for muons : an example
- → Fundamental issues
- → Proposed compact ring
- → Investigators

Particle Accelerators to date have taken full advantage of the microwave part of

THE ELECTROMAGNETIC SPECTRUM



Optical Manipulation of Particle Beams

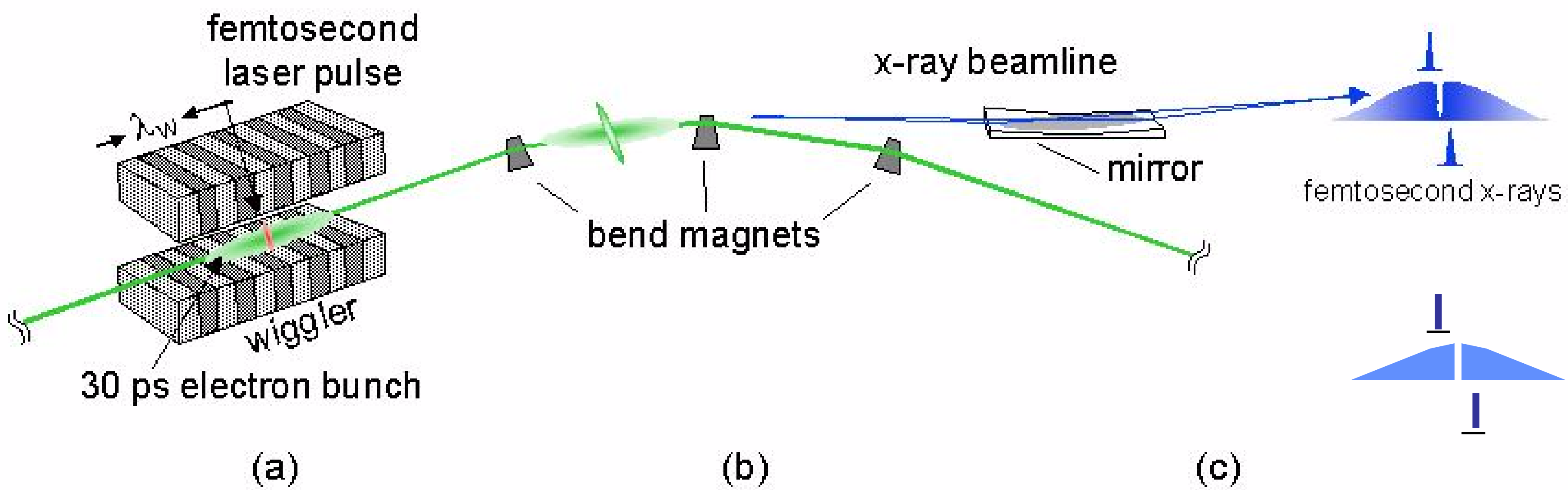
Today we can complement the GHz microwave rf technology by state-of-the-art short pulse high power compact lasers as work horses for particle accelerators.

However, just as in today's microwave technology involving beam manipulation over fractions of mms in time-scales of picoseconds at frequencies of GHz, one would have to learn to manipulate and control signals and particles at optical wavelengths of microns, in time-scales of femtoseconds and at frequencies of THz and higher in order to take advantage of today's optical technology.

The development of femtosecond kickers, choppers, bunch rotators etc., and THz manipulation of beams will be one of the most challenging jobs for future beam applications.

We are encouraged by our recently successful experimental experience.

Laser Femto-slicing of Electron Beams



Reference:
Generation of Femtosecond Pulses of Synchrotron Radiation
R. Schoenlein, S. Chattopadhyay, H.H.W. Chong, T.E. Glover,
P.A. Heimann, C.V. Shank, A.A. Zholents, M.S. Zolotorev
Science, Vol. 287, No. 5461, March 24, 2000, p. 2237.

→ **Unique experiment in the world.**

→ **Berkeley Lab pioneering a new field**
Research: Optical Manipulation of Beams

Applications of Optical Control

- Beam slicing
- Femto-second and atto-second control
  (10^{-15} s) (10^{-18} s)
- Optical diagnostics of beam granularity in phase space
- Luminosity control
- Optical stochastic cooling of phase space:

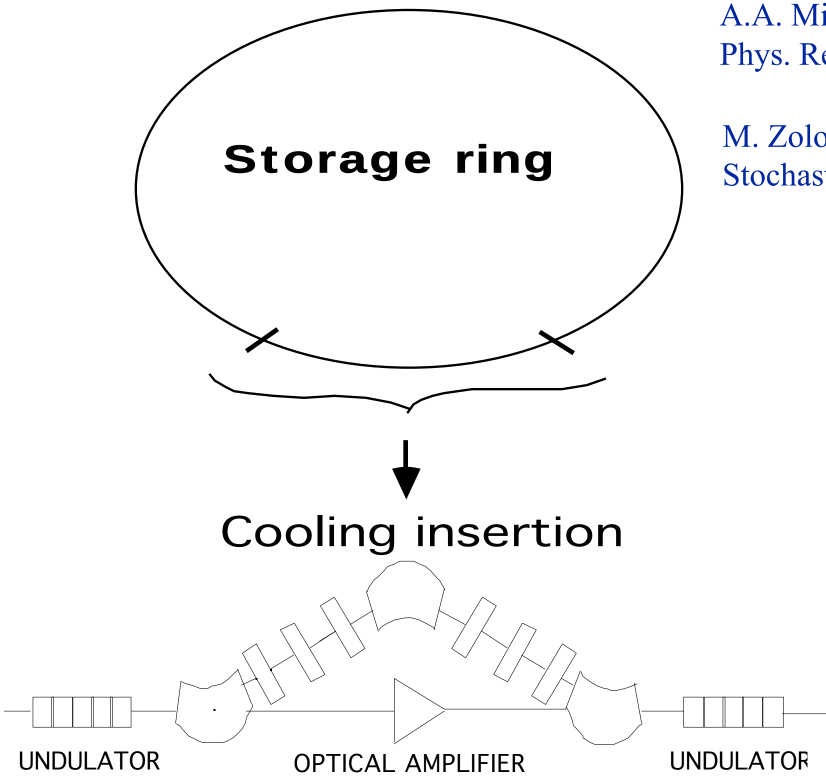
→ Unstable particles : Muons for neutrino sources & muon collider

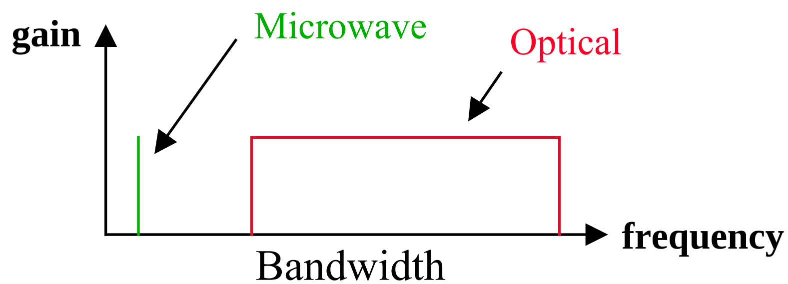
Hadrons : for very large hadron collider

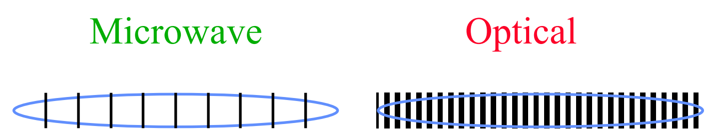
Optical Stochastic Cooling

A.A. Mikhailichenko and M.S. Zolotorev, "*Optical stochastic cooling*", Phys. Rev. Lett. , Vol. .71, N25, (1993), p. 4146.

M. Zolotorev and A. Zholents, "Transit-time Method of Optical Stochastic Cooling", Phys. Rev. E, Vol. 50, No. 4, (1994), p. 3087.







OSC uses optical amplifier and undulators as a pick-up and a kicker.

The amplifier bandwidth is $\sim 10^{13}$ Hz.

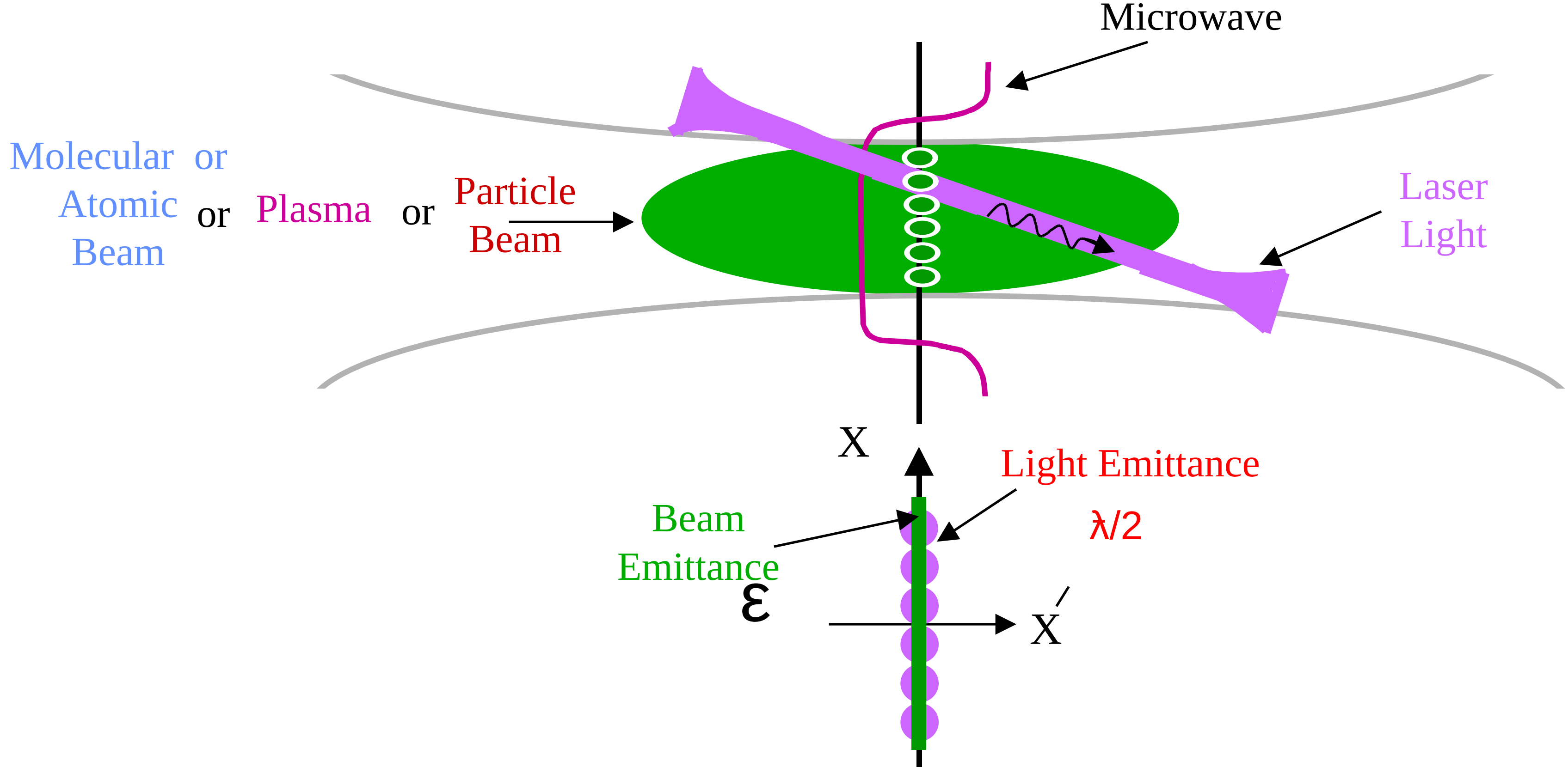
(Compare with $\sim 10^{9}$ Hz for microwave stochastic cooling)

Correspondingly, OSC has a potential for $\sim 10^{4}$ faster damping.

Particle Beam is fully Resolved in Space & Time by Light Beam

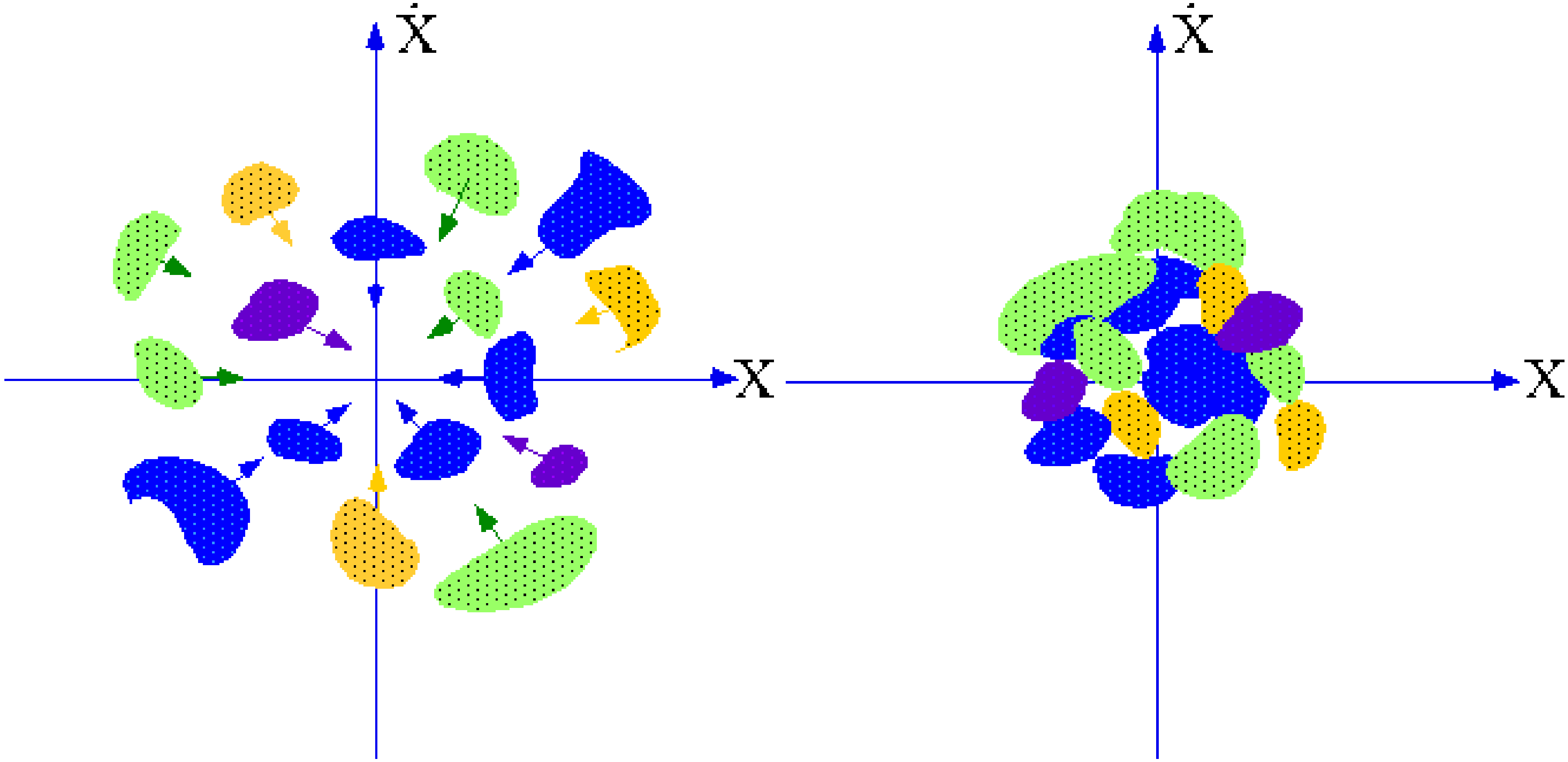
Cooling Rate $< \tau >^{-1}$ α Degree of Control in Phase Space α Number of Independent Phase Space Samples Probed $\equiv \frac{N}{N_s}$

Cooling Time $N_s \equiv$ No. of Particles in a Sample



Coherence Volume of Light << Beam Emittance

Phase-Space Cooling in Any One Dimension



A Particular List of Parameters for a 2 TeV x 2 TeV Muon Collider Utilizing Optical Stochastic Cooling

	Units	This Study	CDR Ref.[8]
Beam energy	TeV	2	2
Circumference	km	8.08	8.08
Number of muons		4.5×10^{8}	2×10^{12}
Number of bunches of each sign		2	2
Beta-function at the IP	μm	10	3000
Bunch length	μm	10	3000
Peak current	kA	2	32
Transverse beam size at the IP	μm	1.3×10^{-3}	3
Beam divergence at the IP		1.3×10^{-4}	1×10^{-3}
Beam energy spread		1×10^{-3}	7×10^{-4}
Beam-beam parameter		0.15	0.045
Repetition rate	Hz	200	15
Luminosity	$Cm^{-2}s^{-1}$	1×10^{35}	1×10^{35}

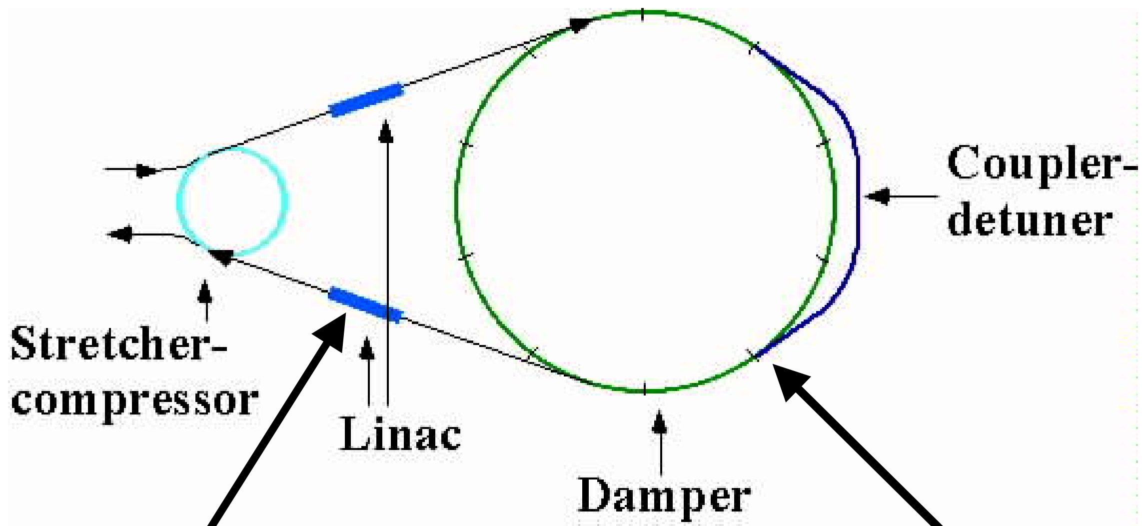
Parameters for Muon Cooling

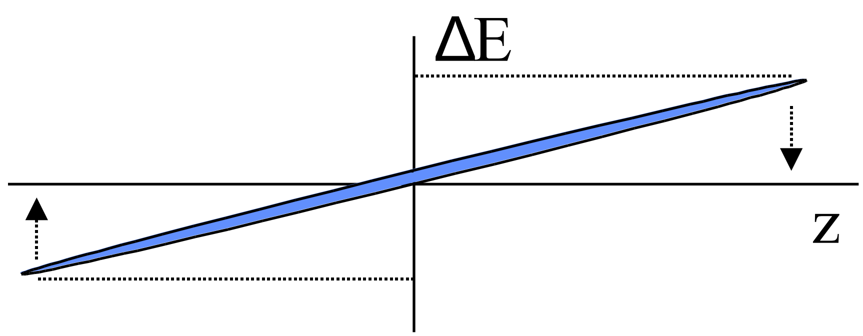
	Units	Value
Beam energy	GeV	100
Repetition rate	Hz	200
Input beam characteristics		
Number of muons		3×10^{9}
Transverse emittance	cm-rad	2×10^{-3}
Longitudinal emittance, $\gamma\sigma_z\sigma_e$	cm	20
Beam energy spread, σ_e		1×10^{-3}
Bunch length, σ_z	cm	20
Stretcher-compressor		
Circumference	m	300
Momentum compaction		0.33
Induction linac		
Pulse duration	μs	1
Energy gain	MeV	±125
Damping rings		
Circumference	m	1100
Number of rings		3
Number of injected muons		2×10^{9}
Beam energy spread, σ_e		2×10^{-6}

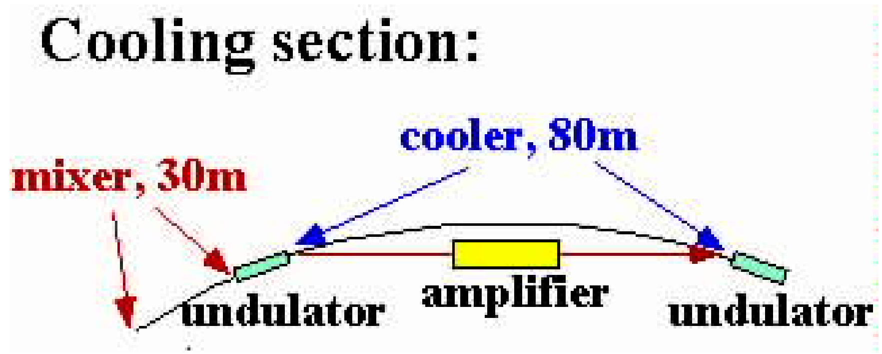
Parameters for Muon Cooling, *cont'd*

	Units	Value
Bunch length, σ_z	m	100
Number of sample particles		25
Longitudinal damping time	turns	75
Transverse damping time	turns	30
Undulator period	cm	50
Peak undulator field	T	10
Number of periods		14
Dispersion function	m	100
Beta function	m	2
Optical amplifier		
Number of amplifiers		10
Amplified light energy	J	1
Average output power	W	200
Amplitude gain		3.8×10^{4}
Wavelength	nm	800
Output beam characteristics		
Number of beams		4.5×10^{8}
Transverse emittance	cm-rad	3×10^{-7}
Longitudinal emittance	cm	2×10^{-2}
Cooling time	ms	4

A Scheme for Optical Stochastic Cooling of Muons







Fundamental Issues

We expect: $< \tau >^{-1}$ $\dfrac{1}{[N_s]}$ cooling time

But, in practice, there is always amplifier noise which modifies cooling rate to :

$$< \tau >^{-1} \quad \frac{1}{[N_s + N_n]}$$

where $N_n \equiv$ sample population that can generate a noise signal equivalent to the optical amplifier noise

→ → → → What is N_n ?

Fundamental Issues

Each particle emits ‘α’ photons per turn, where $\alpha \equiv$ fine structure constant ~ 1/137

Total no. of equivalent noise photons is ~ αN_n

Fundamental Issues

Theoretical minimum of optical amplifier noise is one noise photon per optical mode :

$$\alpha N_n \sim 1 \Rightarrow N_n = 1/\alpha$$

$$< \tau >^{-1} \simeq \frac{1}{[N_s + (1/\alpha)]}$$

Fundamental Issues

For large sample population, $N_s \sim 10^7 - 10^9$,
the number of equivalent
photons from sample and amplifier :

$$N_p = \alpha\, N_s + \alpha N_n \sim (10^5 - 10^7) + 1 >> 1.$$

This large no. of photons generate an electric field in the far-field regime which is describable as classical light

Large "degeneracy parameter": large number of photons in a coherence volume

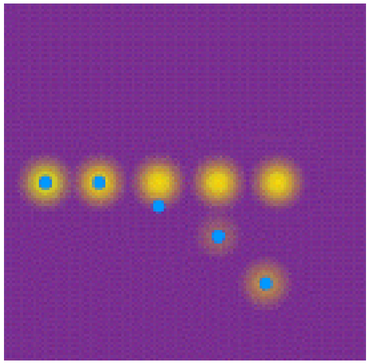
Fundamental Issues

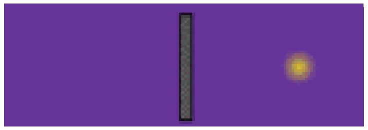
For small sample population, $N_s \sim 50 - 100$,
the number of equivalent
photons from sample and amplifier :
$N_p \sim (0.5 - 1) + 1 \sim O(1)$.
These few photons generate a field which
is intrinsically non -classical and quantum mechanical.

Small "degeneracy parameter": small number of photons in a coherence volume

How does stochastic cooling work in
this quantum limit ??

Radiation for Charged Particles— A Simple Physical Vision





http://www.lbl.gov/educational sites/The World of Beams

Proposed Compact Storage Ring

- **Feasibility of optical stochastic cooling**
- **Explore the physics of stochastic cooling at the quantum limit**
- **Scaled beam dynamics of LVHC at high time-shift limit of $\Delta\nu \sim$ •1**
- **Technology of permanent magnet technology**
- **Optical manipulation of beams**
- **Optical diagnostics of THz frequencies**

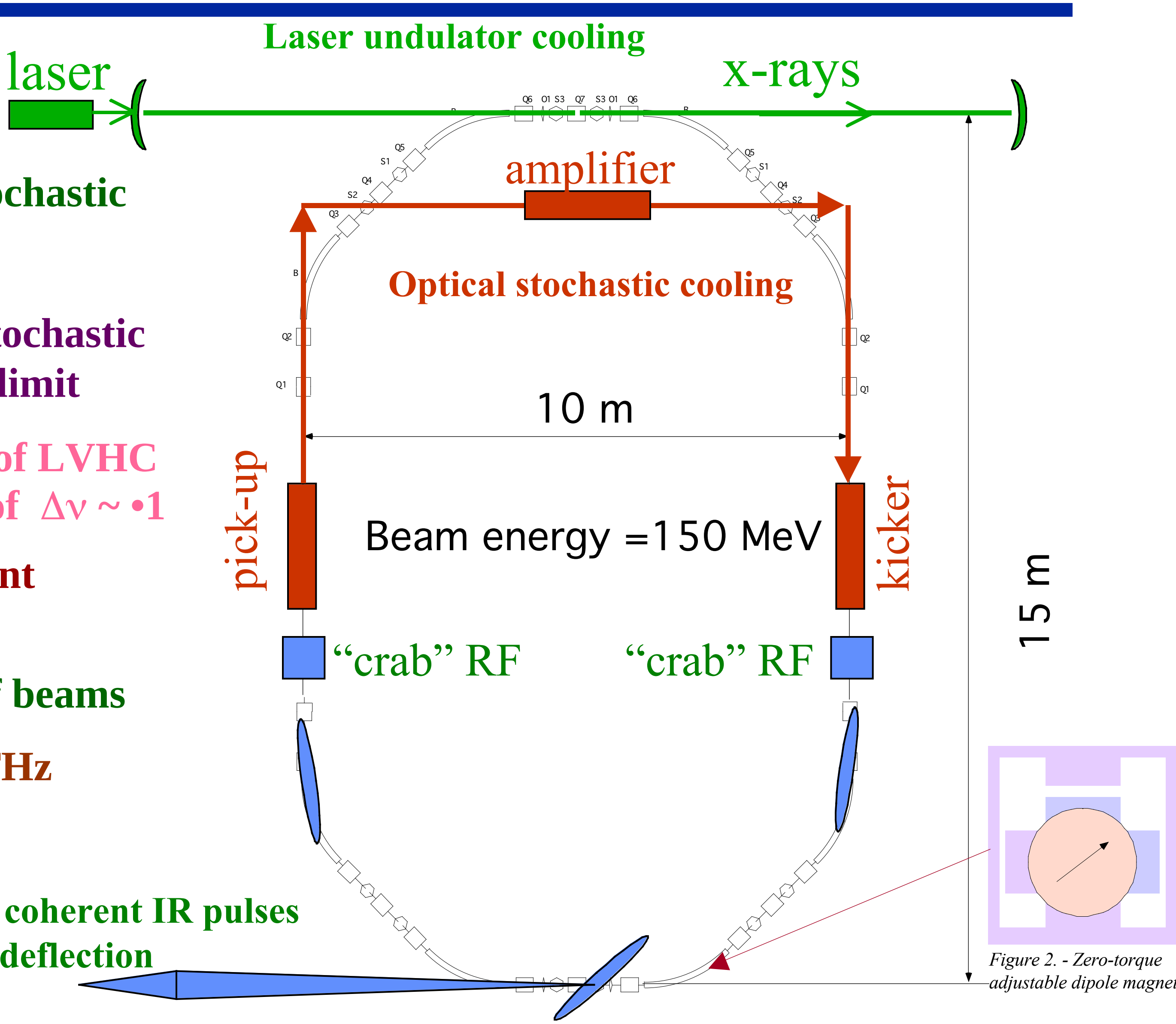


Figure 2. - Zero-torque adjustable dipole magnet.

Investigators

S. Chattopadhyay
W. Barletta
(Physics goals and oversight)

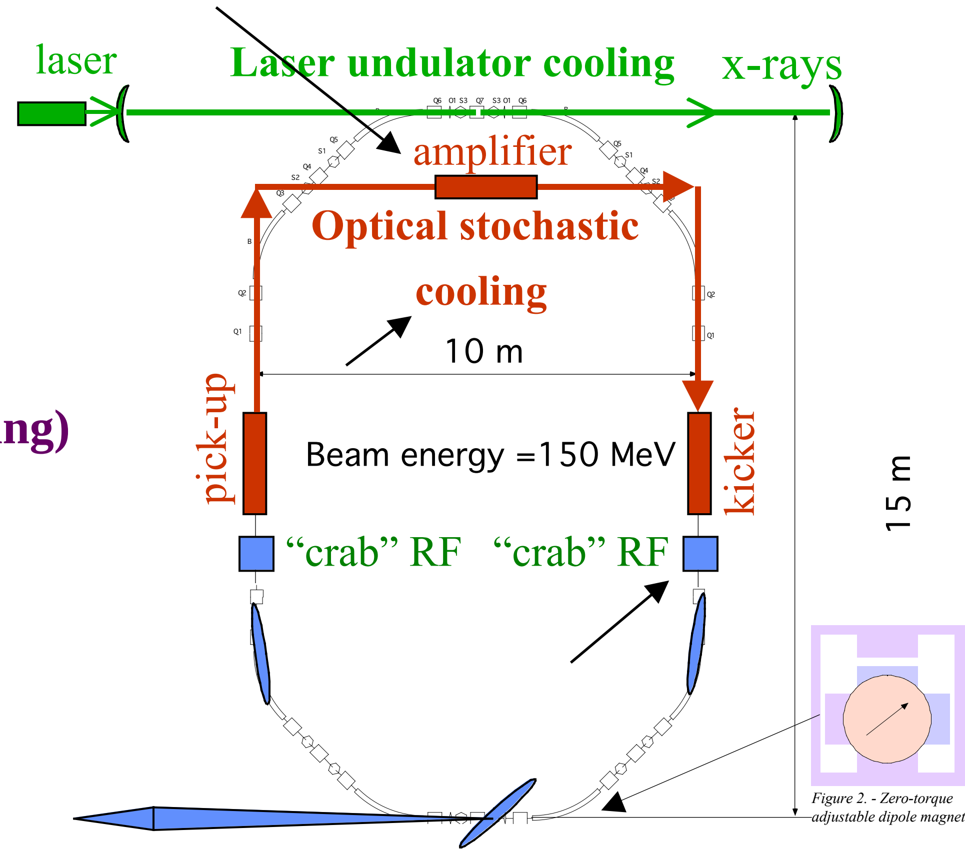
K. Robinson (Permanent Magnets)

A. Zholents
M. Zolotorev
(Optical Stochastic Cooling)

W. Leemans (Laser)

J. Corlett (Microwave)

A. Jackson (Magnets and Lattice)



Femtosecond coherent IR pulses via RF orbit deflection

Proposed Compact Storage Ring

- Design is under way

- Cost goal ~ $5M - $10M + Operating

- Proposed ring complements existing national linac-based facilities at other labs.

- Brings in science and technology issues that are critical to HEP and cannot be addressed elsewhere (requires storage ring based facility).

- Unique Berkeley Lab proposal based on current R&D optical technology, not duplicated by work elsewhere.